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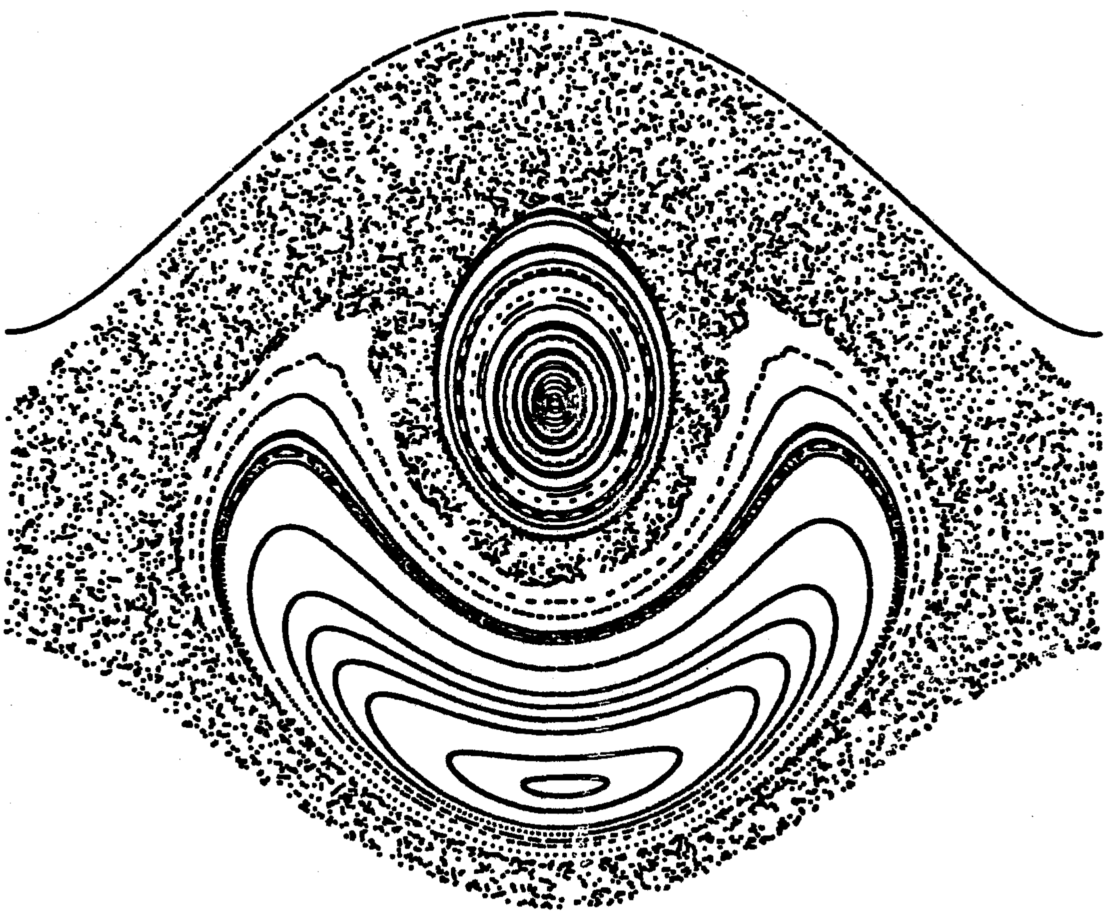

LARGE HADRON COLLIDERS

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ABSTRACT

A review of some of the accelerator physics issues which arise in the design of the contemporary large hadron colliders discusses the following topics: Survey of Hadron Colliders, Primary Constraints, Magnet Style, and Dipole Field Errors.

1. INTRODUCTION

The first two high energy proton accelerators to be brought into storage ring operation, the ISR and the SPS, were built using conventional iron dominated magnets. In order to reduce the power consumption, and to achieve fields above the saturation limit of iron, contemporary proton storage rings use superconducting magnets, whether they exist (TEV), are under construction (HERA, SSC), or are in the design phase (LHC, RHIC, UNK). Another significant trend is that the number of circulating bunches which must be stored in order to achieve useful luminosities increases dramatically, as energies rise and colliders get longer. There are about 15,000 bunches in the SSC. A "large hadron collider" is defined, for the purposes of this discussion, as using superconducting magnets, and storing very many bunches per beam. Both of these assumptions have fundamental consequences. For example, the magnetic field quality is significantly worse in superconducting magnets than in conventional magnets.

The discussion which follows concentrates on selected issues which dominate large hadron collider design. Some important issues (such as collective effects) are ignored, and some (such as the beam-beam interaction) are merely sketched, in order to retain pedagogical clarity within the space available.

2. SURVEY OF HADRON COLLIDERS

The list of the worlds' large hadron colliders shown in Table 1 reveals a healthy diversity of particle species, and accelerator parameters, reflecting the spectrum of high energy physics goals that they seek to address. Only CERN's Super Proton Synchrotron (SPS), the oldest of the machines, and DESY's HERA-e, which is not a hadron collider, do not use superconducting (SC) technology. These colliders are included in the table for the sake of completeness. It is significant that the only two colliders to use antiparticles (antiprotons), the SPS and Fermilab's Tevatron, are also the only two colliders currently in operation. As is discussed in more detail below, the designers of future colliders avoid the difficulties of producing antiprotons, at the cost of complicating the magnet design, in order to achieve higher luminosities.

Asymmetric beams of electrons and protons will collide in HERA, at collisions points where the beams in two very different rings, HERA-e and HERA-p, will cross.

CERN's Large Hadron Collider, the LHC, lies in the LEP tunnel, and thus has a well defined circumference, and a somewhat constrained geometry.

Collider name	Particle species	Magnet type	B field (Tesla)	Energy (TeV)	Circumference (kilometers)	Finish date
(HERA-e	e	conventional	.18	.030	6.3	built)
HERA-p	p	SC	4.5	.82	6.3	1991
LHC	p-p	SC	8.0 ?	7.0 ?	27.3	1997
RHIC	ions	SC	3.5	Au: 0.1u	3.8	1996
SPS	p-$\bar{p}$	conventional	1.8	.45	6.9	built
SSC	p-p	SC	6.6	20.0	86.3	1997
Tevatron	p-$\bar{p}$	SC	4.3	.95	6.3	built
UNK	p-p	SC	5.0	3.0	21.0	1997

Table 1 General parameters of contemporary large hadron colliders

Brookhaven's Relativistic Heavy Ion Collider, RHIC, is perhaps the most exotic of the colliders in the list. It will collides a range of species of ions, with a momentum per atomic mass number of 100 GeV/c, in the case of gold.

The Superconducting Super Collider, SSC, is under construction just south of Dallas, Texas, and has the highest energy and the largest circumference of all the colliders quoted.

UNK is an accelerator presently under construction in the Soviet Union, at the Serpukhov laboratory near Moscow.

The nominal time scale for these projects, show in the finish dates, suggests that most will come to fruition towards the close of the twentieth century. Only HERA will become active in the first half of the 1990's, to stand in the limelight as the worlds most modern hadron collider for at least five years. Accelerator physicists will learn a great deal from the commissioning and operation of HERA, just as a great deal has already been learnt from the Tevatron, the worlds first superconducting hadron collider.

3. PRIMARY CONSTRAINTS

Suppose that the design goal of a hadron collider is to reach a given luminosity at a given storage energy, with a given normalized emittance. The luminosity for head on collisions at a single interaction point is

$$L = \frac{N_B^2}{S_B} \frac{c}{4\pi\sigma^{*2}} \qquad 1$$

where c is the speed of light, σ^* is the root mean square transverse beam size (assuming the same Gaussian distribution in both dimensions), N_B is the bunch population, and S_B

is the longitudinal spacing between bunches in one beam. The bunch spacing must be reduced as far as possible, in order to make large luminosities with reasonable bunch populations which will not, for example, violate beam-beam dynamical limits. Another reason to reduce S_B at fixed luminosity is in order to reduce the average number of events per crossing,

$$\langle n \rangle \quad = \quad L\, S_B \,\frac{\Sigma_{inel}}{c} \qquad\qquad 2$$

to a level which can be tolerated by the experiments. Some experiments may only be able to interpret one event per interaction. The total proton-proton inelastic cross section Σ_{inel} is expected to be about 90 millibarns at SSC energies.

As the bunch spacing is decreased at fixed luminosity, the total beam current $I \sim N_B/S_B$ increases, since $L \sim I^2 S_B$. This has unfortunate consequences if synchrotron radiation is significant, since the total radiated power per ring is

$$P \quad = \quad \frac{Z_0}{3}\,\frac{e^2 c^2 \gamma^4}{C\rho}\; N_T \qquad\qquad 3$$

where Z_0 is the impedance of free space, e is the electronic charge, γ is the usual relativistic factor, C is the ring circumference, ρ is the bending radius, and N_T is the total population in one beam. This heat load must be removed by the cryogenic refrigeration system cooling the vacuum pipe, with significant cost implications. Another limit to short bunch spacing is the ability of the experiments to reset their electronics in the time available between bunch crossings.

Short bunch spacing means that there are typically tens of locations in an interaction region, separated longitudinally by $S_B/2$, where parasitic collisions may occur. This mandates the introduction of a crossing angle at the principal collision point, since the experimenters want collisions at only one place. Worse, without a crossing angle the cumulative beam-beam interaction effects are usually intolerable, since the tune shift at each head on collision is

$$\Delta\nu_{HO} \quad = \quad \xi \quad \equiv \quad -\frac{N_B r_p}{4\pi\varepsilon} \qquad\qquad 4$$

where ξ is the beam-beam tune shift parameter, r_p is the classical proton radius, and ε is the invariant emittance. When the crossing angle α is large compared to σ^*/β^*, the angular size of the beam at the interaction point, then in addition to the single head on tune shift given by (4), there is also a long range tune shift, due to a total of n_c collisions per interaction region, which is well approximated by

$$\Delta\nu_{LR} \quad = \quad n_c\; \xi\; \frac{2}{[\,\alpha\,/\,(\sigma^*/\beta^*)\,]^{\,2}} \qquad\qquad 5$$

The head on tune shift is proportional to the bunch population N_B, while the long range shift depends on the total population N_T, so that varying the bunch separation trades one off against the other.

When the crossing angle is large compared to σ^*/σ_s, the aspect ratio of the beam, a significant loss of luminosity results, because the longitudinal tails of the bunches do not collide. The ratio of the true luminosity to the head on luminosity is given by

$$\frac{L}{L_0} = [\, 1 + (\alpha \frac{\sigma_s}{2\sigma^*})^2 \,]^{-\frac{1}{2}} \qquad 6$$

Attempts to increase the true luminosity by continuously reducing β^* (and hence σ^*) eventually run into a conflict between the need for α to be large to control the long range tune shift, and the need for α to be small in order to achieve a reasonable fraction of the available head on luminosity. Angles much smaller than the longitudinal aspect ratio are also preferred for beam-beam reasons, because odd resonances and satellite resonances are then partially suppressed.

4. MAGNET STYLE

If large numbers of nominal intensity bunches in each counter-rotating beam are allowed to pass through each other head on, at locations all around a collider, the cumulative beam-beam effect is disastrous. Left unsolved, this problem limits the attainable luminosity, since either the number of bunches or their intensity must be reduced. Two solutions are possible - separate the orbits of the two beams in a single vacuum pipe, or separate them into two vacuum pipes. When the counter-rotating beams are separated into two different magnet bores, long range beam-beam collisions only occur near the interaction points. Their effect is then of only secondary importance, except when collider performance is pushed to its ultimate limits.

Separation of orbits inside a single magnet bore has the advantage of requiring fewer magnets - or, at least, requiring simpler magnets, since a single dipole magnet may contain two bores. However, the long-range beam-beam interactions which are still present, although greatly reduced in strength, still limit the attainable luminosity. Hence, this solution has not been adopted for any of the large hadron colliders in currently in design or construction. It has been adopted as an upgrade strategy in both of the existing hadron colliders, the SPS and the Tevatron, the only two contemporary colliders colliding particles with antiparticles. The residual limitation on the number of bunches is not of great concern in these machines, since the limited numbers of antiprotons available are anyway most efficiently employed in a relatively small number of bunches. Table 2 shows very clearly the correlation between a single bore and a small number of bunches. The apparent exception to this rule is RHIC, which uses a relatively small number of bunches to concentrate the limited number of heavy ions available.

Assuming from here on the (now conventional) design choice of separating two beams of identical species into two bores, the question of choosing one or two magnets still remains. In a typical "two-in-one" dipole magnet, two bores in a single magnet are horizontally separated in the mid-plane of the magnet, so that the flux passing up through one bore goes down through the other. The shared flux means that slightly higher fields are reached more easily, but also means that the two beams are magnetically coupled. This coupling is a potential source for serious operational difficulties, since not only will the two rings share magnetic errors, but also the corrections applied to the two rings tend not be orthogonal. However, the total heat leak per meter is less than for two separate magnets, and the total cross-sectional space occupied in the tunnel is less. It is because of the compactness of this solution that it has been adopted for the LHC, which must share a tunnel with the LEP. Table 2 shows that, in contrast, the other comparable colliders (RHIC, SSC, and UNK) all use two independent magnets.

Name	Species	Number of				Comment
		BUNCHES	BORES	MAGS	CRYOS	
HERA	e-p	210	2	1+1	1	one ring normal
LHC	p-p	10,000 ?	2	1	1	space constraint
RHIC	ions	Au: 57	2	2	2	horizontal separation
SPS	p-$\bar{p}$	12	1	1	-	horizontal pretzels
SSC	p-p	15,000	2	2	2	vertical separation
TeV	p-$\bar{p}$	36	1	1	1	helical orbits
UNK	p-p	12,000	2	2	2	horizontal separation

Table 2 Magnet styles in contemporary hadron colliders

Independent "one-in-one" magnets have the virtue of simplicity of design, and of independent operation. They may be placed side by side, or one on top of the other. The magnetic errors of each ring are independent, as are the misalignment errors, and the beam separation may be increased at will, above a minimum value. One ring may be operated independently of the other, perhaps even at a different energy. If two magnets are chosen, there is still the question of using one or two cryostats - two magnets could be enclosed in a single cryostat. However, as Table 2 shows, in practice each magnet is assigned its own cryostat.

A vertical separation of two one-in-one rings has the advantage of simpler beam injection and abort, easier magnet installation and change procedures, and more efficient use of tunnel floor space. Horizontal separation has the slight advantage of making dispersion control easier at the collision points, but makes it difficult to match the two ring circumferences when the IRs are "clustered" with an even number of IRs in each cluster.

None of the arguments presented here conclusively favor one or other magnet construction style, or separation orientation.

5. DIPOLE FIELD ERRORS

The two dimensional field in any magnet can be specified by a multipole expansion according to

$$B_y + i\,B_x \;=\; B_0 \sum_{n=0}^{\infty} (b_n + ia_n)\,(x + iy)^n \qquad 7$$

For example, a perfect dipole has $b_0=1$, and a perfect skew quadrupole has $a_1=1$, with all other terms zero. This notation also lends itself naturally to a description of magnetic field errors in dipoles, which are the dominant sources of optical errors in large hadron colliders. The normal and skew coefficients b_n and a_n can be derived almost directly from Fourier analysis of the voltage on a rotating coil inside a magnet.

Conventional "iron dominated" magnets are limited in the field they can attain to the saturation field of their laminations, about 2 Tesla. If the laminations do not saturate - so that their relative permeability is very much larger than one - the magnetic field is constrained to be normal to the surface of the pole tips. This simple boundary condition, and the precision with which laminations can be stamped and aligned, results in the high field quality usually associated with iron dominated magnets. The boundary conditions in superconducting "current dominated" magnets is, by contrast, relatively awkward. It is easy to show that a thin circular current shell, with a density proportional to $\cos(\theta)$, where θ is the azimuthal angle, results in a perfect dipole field. However, in a realistic "cosine theta" magnet the distribution of conductors is not thin, and it is not trivial to design even an idealized coil which will suppress several low order systematic multipole fields. In operation, the conductor braids must not slip relative to each other or their mechanical supports, despite the large forces to which they are subjected, otherwise the magnet will quench. Their cross-sectional size is subject to fluctuation, and they are harder than laminations to place accurately. Even if all these practical problems could be overcome, the fundamental phenomenon of "persistent currents" in the filaments, discussed below, causes fields which are both hysteretic and time dependent.

Random contributions to the normal and skew multipole coefficients come from conductor placement errors, and from the spread in the distribution of filament sizes and critical currents. Measurements on many different superconducting dipoles of various bore diameters d have lead to an empirical scaling of the coefficients,

$$\langle a_n^2\rangle^{\frac{1}{2}}, \quad \langle b_n^2\rangle^{\frac{1}{2}} \quad \sim \quad d^{\,-n-\frac{1}{2}} \qquad 8$$

which is also in good agreement with theoretical models of construction errors. The physical meaning of this scaling is expressed as a rule of thumb which ignores the $-1/2$ term in the exponent: the fraction of the bore containing good field quality is independent of the bore size. Another rule of thumb is that random field errors are not significant contributors to betatron tune shifts with amplitude, but are dominant contributors to resonance effects, such as the distortion of phase space orbits away from linear behavior.

Systematic contributions to even order normal multipole coefficients, b_{2n}, come from persistent current magnetization in the superconducting wires, from saturation in the iron in the cryostat, and from systematic conductor placement errors. The strongest of these sources is the persistent current effect. Here, each individual superconducting filament partially excludes magnetic flux by rearranging its internal current distribution, so that more current flows down one side of the filament than the other. This nonuniform current distribution depends on the history of the filament - persistent current multipole fields exhibit hysteresis. Less flux can be excluded at higher fields, so that the problem is most severe at the injection energy of a collider. One way to alleviate the situation is to use the smallest possible filament diameter. Other ways are to raise the injection energy (and field), and to enlarge the bore of the magnet.

The worst property of systematic errors is their ability to cause large tune shift variations with particle betatron amplitude A_β, and with δ, the momentum offset. The horizontal tune shift due to an error b_n is

$$\Delta\nu_n = b_n \left\langle \beta \cos(\phi) \left[\eta\delta + A_\beta (\beta/\beta_{max})^{1/2} \cos(\phi)\right]^n \right\rangle \qquad 9$$

where two independent averages are taken, over the phase of a betatron oscillation ϕ, and over the beta and dispersion values. In a "smooth" approximation, where β and η take on their average cell values, this reduces to

$$\Delta\nu_n = b_n\beta \sum_i 4^{-i-1}\, C^n_{2i+1}\, C^{2i+2}_{i+1}\, A_\beta^{2i}\, (\eta\delta)^{n-2i-1} \qquad 10$$

where

$$C^i_j \equiv \frac{i}{j!\,(i-j)!} \qquad 11$$

These simple expressions demonstrate that the effects of systematic dipole errors are easier to calculate than those of random errors, whose analysis relies on computer simulation.

Operationally, systematic errors are much easier to diagnose and correct than random errors. This is fortunate, because the strong persistent current multipole fields not only exhibit hysteresis, but also decay with time. The flux pinning centers, which are responsible at a quantum mechanical level for maintaining the current distribution, are subject to diffusion. These pinning centers are a feature of Type II superconductors, which permit the penetration of a flux quantum by energetically favoring its passage through a small island of normal material, surrounded by a sea of superconductivity. When the dipole field is held constant, during an injection phase typically lasting tens of minutes, the persistent current sextupole component (for example) drifts according to the logarithm of the time. However, as soon as the main field starts to rise, at the beginning of the energy ramp, the sextupole component quickly snaps back almost to its original value. This rapid change in the nonlinear behavior of hadron colliders is a major operational impediment, which has still to be completely understood and controlled. A special feedback circuit is being created at the Tevatron for this purpose.

It is good to end on this challenging note. Large hadron colliders are by no means as boring and "conventional" as some more daring accelerator physicists would have us believe. They still present important and intriguing problems whose proper analysis requires the development of radically new techniques.